Faraday Rotation Measure Gradients from a Helical Magnetic Field in 3C 273

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ABSTRACT

Using high frequency (12-22 GHz) VLBA observations we confirm the existence of a Faraday rotation measure gradient transverse to the jet axis of the quasar 3C 273. This transverse rotation measure gradient is expected if a helical magnetic field wraps around the jet. The overall order to the magnetic field in the inner projected 40 parsecs is consistent with a helical field. However, we find an unexpected increase in fractional polarization along the rotation measure gradient. This high fractional polarization observed along the RM gradient rules out internal Faraday rotation, but is not readily explained by a helical field. The presence or absence of transverse rotation measure gradients in other sources is also discussed. After correcting for the rotation measure, the intrinsic magnetic field direction in the jet of 3C 273 changes from parallel to nearly perpendicular to the projected jet motion at two locations. If a helical magnetic field causes the observed rotation measure gradient then the synchrotron emitting electrons must be separate from the helical field region.

Subject headings: galaxies: active – galaxies: quasars: individual (3C 273) – galaxies: jets – radio continuum: galaxies – polarization

1. Introduction

How jets are launched by massive black holes remains one of the fundamental unsolved issues in astrophysics. Many researchers have suggested that magnetic fields are intimately

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involved in the collimation of the jet and could determine which sources have prominent jets and which do not (Meier, Koide, & Uchida 2001; Koide et al. 2002). Blandford (1993) urged observers to search for Faraday rotation measure (RM) gradients transverse to the relativistic jet. Such a gradient is expected if a helical magnetic field wraps around the jet, and among other effects, creates a Faraday screen. For a source with a jet axis in the plane of the sky a helical field wrapping around a jet produces a maximum line-of-sight components along the jet boundary, no net line-of-sight magnetic field component at the center. Blandford realized that this would produce a gradient in the observed RM across the jet. Projection effects for inclined jets produce an offset in the RM (Asada et al. 2002) while preserving an RM gradient.

Faraday rotation measure gradients in 3C 273 (Asada et al. 2002) based on 5-8 GHz VLBA observations, present intriguing evidence for one source in which we may be able to see the effects of helically wound fields, and measure the sense of rotation of an accreting black hole. With the search for these RM gradients in mind, we have reanalyzed 12-22 GHz VLBA polarimetry observations for two epochs on 3C 273 to obtain higher angular resolution transverse to the jet axis, while maintaining good sensitivity to the faint polarized emission.

Throughout this discussion, we assume H_0=71 km s^{-1} Mpc^{-1} (Spergel et al. 2003), Ω_M = 0.27, and Ω_Λ= 0.73. This gives a scale for 3C 273 of 1 mas = 2.52 pc.

2. Observations and Results

The observations were made on 2000 January 27 (2000.07) and 2000 August 11 (2000.61) with the ten element Very Long Baseline Array (VLBA)[1]. Data reduction and calibration for the 2000.07 epoch were discussed in Zavala & Taylor (2001). We re-examined the data for 2000.07 and made polarization angle maps using using five frequencies: 12.1, 12.6, 14.9, 15.4 and 22.2 GHz. The observational setup for the 2000.07 observation was repeated for the 2000.61 epoch. The same data reduction and calibration procedures of 2000.07 (Zavala & Taylor 2001) were applied to the 2000.61 data. A datacube of polarization position angle maps ordered in λ^2 was used to create the rotation measure maps. Pixels in the RM maps were blanked if the polarization position angle error was more than $\pm$ 10° at any frequency.

Rotation measure images for the two epochs are presented in Figure 1a (2000.07) and Figure 1b (2000.61). Between the two epochs the region immediately southwest of the Stokes

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I peak (i.e. in the projected direction of the jet) shows a change in RM. At 2000.07 the RM is ≈ 1800 rad m^{-2} and 6 months later shows a south to north gradient with an RM from -1000 to $+1000$ rad m^{-2}.

Beyond 3 mas from the Stokes I peak (hereafter this region is referred to as the "jet") the RM distribution becomes smoother and does not change dramatically between the two epochs. The mean RM for the jet is 642 rad m^{-2} for the 2000.07 epoch, and 652 rad m^{-2} for 2000.61. An RM gradient transverse to the jet is apparent, and we discuss this in §3.1.

In Figure 2 we show the RM corrected intrinsic B vectors for 3C 273 under the assumption that the source is optically thin from 12-22 GHz. We simply took the Faraday corrected E vectors and rotated them by 90 degrees. This was done for the entire jet, and for the core west of the Stokes I peak. This does not take relativistic aberration into account (Lyutikov, Pariev, & Blandford 2003; Lyutikov, Pariev, & Gabuzda 2004) which could change the orientation of the B vectors by up to 20°. The jet B vectors are initially oriented roughly parallel to the projected jet direction, then rotate to almost a N−S orientation 6 mas southwest of the Stokes I peak. This changing B vector orientation repeats itself as we move beyond 6 mas from the Stokes I peak. For the 2000.61 epoch we detected polarization as far as 15 mas down the jet, and the B vectors there have returned to a direction parallel to the projected jet axis.

3. The changing Faraday screen in 3C 273

In Fig. 1 we noted the change in the RM at 3 mas southwest of the Stokes I peak. What causes the change in the observed RM? 1 mas corresponds to a projected distance of 2.5 parsecs at the redshift of 3C 273. A region of that size is unlikely to change over a six month time interval. We thus reject a change in the physical conditions of a foreground Faraday screen as the cause of the changing rotation measure. A more likely explanation for the RM changes over the 6 month time interval is a moving polarized component seen through a foreground Faraday screen which has structures on sub-parsec to parsec scales. Small scale polarization structure in 3C 273 at 43 and 86 GHz (Attridge et al. 2003) supports this interpretation. For the region three mas southwest of the Stokes I peak this would require motions of approximately a milliarcsecond over 6 months. This appears to be consistent with the kinematics of components observed from 1995-2001 at 15 GHz in 3C 273 (Ros et al. 2002).

The Faraday screen in front of the jet appears to be relatively constant in time as the RM does not significantly change over the 6 month interval presented here, or over three years (Zavala & Taylor 2001). The jet Faraday screen is also spatially uniform, as opposed to the sub-structure seen in the core (Fig. 1). The more uniform Faraday screen begins at a projected distance of approximately 10 parsecs from the core (Fig. 1). This may be the distance from the central engine beyond which the magnetic field in the Faraday screen has become more uniform and smooth.

3.1. Evidence for a systematic RM Gradient

We now examine the case for a transverse RM gradient as suggested by Blandford (1993). We wish to take a slice across the broadest RM distribution in the jet transverse to the jet motion. We use Ros et al. (2002) to define the jet motion. One might assume that the projected motion of the jet components follows a curved trajectory as suggested by the curvature of the jet in total intensity in Figures 1 and 2. However, Ros et al. show that component motions are almost directly southwest and show no curved trajectories. In Figure 1 we show the locations of the slices across the jet, with the orientation of the slice perpendicular to the line connecting the Stokes I peak of the component at a relative RA= -3 mas, relative $\delta = -6.5$ mas and the map center. Figure 3 shows the resulting RM of the slices at the two epochs: 2000.07 by the dashed line and 2000.61 by the solid line. A transverse gradient of approximately 500 rad m^{-2} mas^{-1} is visible in Figure 3, with almost 4 beamwidths along the gradient. This is much larger than the gradient of 35 rad m^{-2} mas^{-1} across almost two beamwidths obtained with the coarser resolution of Asada et al. (2002). This clearly demonstrates the advantage of working at the highest frequencies the VLBA is capable of, consistent with enough sensitivity to polarized emission. The gradient expected by Blandford (1993) is clearly present, and is suggestive of a helical field wrapping around the jet.

We further note that the RM is predominantly low and mostly negative along the southern edge of the jet in 3C 273 (ignoring a few small and suspect patches of very high RM), even to a distance of 15 mas (38 pc) in epoch 2000.61. Along the northern edge of the source the RMs are larger and predominantly positive. This overall RM structure is consistent with an ordered helical field, and suggests that this field is the dominant source of the Faraday screen on projected linear scales out to at least $\sim$40 pc.

3.2. An Alternative View – Evidence for localized RM enhancements

In Figure 4 we present the 12 GHz fractional polarization along the slices shown in Figure 1. Along with a gradient in the RM we also see a gradient in the fractional polarization.

This indicates that the polarization is more ordered as we proceed from south to north along the transverse RM gradient. Consider the simplest case of a jet in the plane of the sky with a helical magnetic field wrapped around the jet. The fractional polarization should be highest at the jet center, where the RM is zero. The fractional polarization then falls off as we approach either edge of the jet, as the RM depolarizes the underlying emission (Gardner & Whiteoak 1966). Severe projection effects are surely present in 3C 273, yet it is still surprising to see that the highest RM in the jet corresponds to high fractional polarization. Could the localized RM *and* fractional polarization enhancements be the site of an interaction of the jet with the ambient thermal gas which forms the Faraday screen (Bicknell et al. 2003)? In this case the rotation of the B vectors in Figure 2 to approximately perpendicular to the jet motions seen by Ros et al. (2002) could be a compression and enhancement of the local magnetic field due to a collision with the Faraday rotating thermal gas. If such an interaction is responsible for the observed RM and fractional polarization gradients, then the lack of free-free absorption of the jet of 3C 273 may set interesting limits on the electron density of the thermal gas (Zavala & Taylor 2004).

3.3. RM distributions in other sources

Sources with jets broad enough to be well resolved are rare (Pollack, Taylor, & Zavala 2003), but a few examples do exist. The jet of M87 is resolved, but the RM data cover a relatively small area (Zavala & Taylor 2002). There is no obvious RM gradient, but the sign change of M87's rotation measure is consistent with a helical magnetic field. Gabuzda, Murray, & Cronin (2004) report rotation measure gradients in 4 BL Lac sources with an angular resolution comparable to Asada et al. (2002). 3C 147, a compact steep spectrum (CSS) quasar, has a relatively broad jet with an RM gradient observed at 8 GHz (Zhang et al. 2004). The quasars B1611+343 and B2251+158 are well resolved, but there is no evidence of a transverse RM gradient (Zavala & Taylor 2003). BL Lac is marginally resolved and no gradient is apparent (Zavala & Taylor 2003). Another quasar with a resolved jet, B0736+017, fails to display an obvious transverse RM gradient. At present we can say that transverse RM gradients do exist, but these gradients are not a universal feature.

The very high fractional polarization we observe rules out internal Faraday rotation as a cause for the observed RM. Internal Faraday rotation is expected to cause severe depolarization, and discontinuities in the observed position angle versus λ^2 plots (Burn 1966; Tribble 1991). If a helical field is responsible for the observed RM gradient, this implies a segregation of the synchrotron emitting electrons from the helical field region.

4. Summary

We confirm the presence of a transverse rotation measure gradient of 500 rad m^{-2} mas^{-1}, significantly larger than the gradient observed by Asada et al. (2002). This rotation measure gradient, as first suggested by Blandford (1993), is expected if a helical magnetic field wraps around the relativistic jet of 3C 273. This field imposes an order on the Faraday screen which we see as predominantly negative RMs along the south edge and positive RMs along the north edge in the inner projected 40 parsecs of the jet. The increase in fractional polarization along the RM gradient, and turning of the B field vectors from parallel to perpendicular to the projected jet motion, suggest that an interaction may also explain the gradient, although in this case the overall order of the RM distribution has to be explained as a coincidence, or some other mechanism that imposes an overall order to the surrounding magnetic fields. The magnetic field responsible for the Faraday rotation appears to have structure on sub-parsec scales within 3 milliarcseconds (8 pc) from the core of 3C 273. The relatively smooth RM structure of the jet implies a well ordered (on parsec scales) magnetic field in the Faraday screen.

The larger RM gradient and the gradient in fractional polarization structure in 3C 273 revealed by these observations illustrate the advantages of observing broad jets at the highest frequencies at which the VLBA operates. The superb resolution and polarization sensitivity of the VLBA from 12 – 22 GHz enables high spatial resolution tests of theoretical predictions which are key to understanding the physics of relativistic jets. A convincing test of the helical magnetic field model awaits a clear predominance of RM gradients with the expected helicity in many sources, or the detection of a polarized counter-jet with gradients in opposed directions (Asada et al. 2002). If a helical magnetic field is responsible for the observed RM gradients then because the high fractional polarization observed rules out internal Faraday rotation, the synchrotron emitting electrons must somehow be segregated from the helical B field region.

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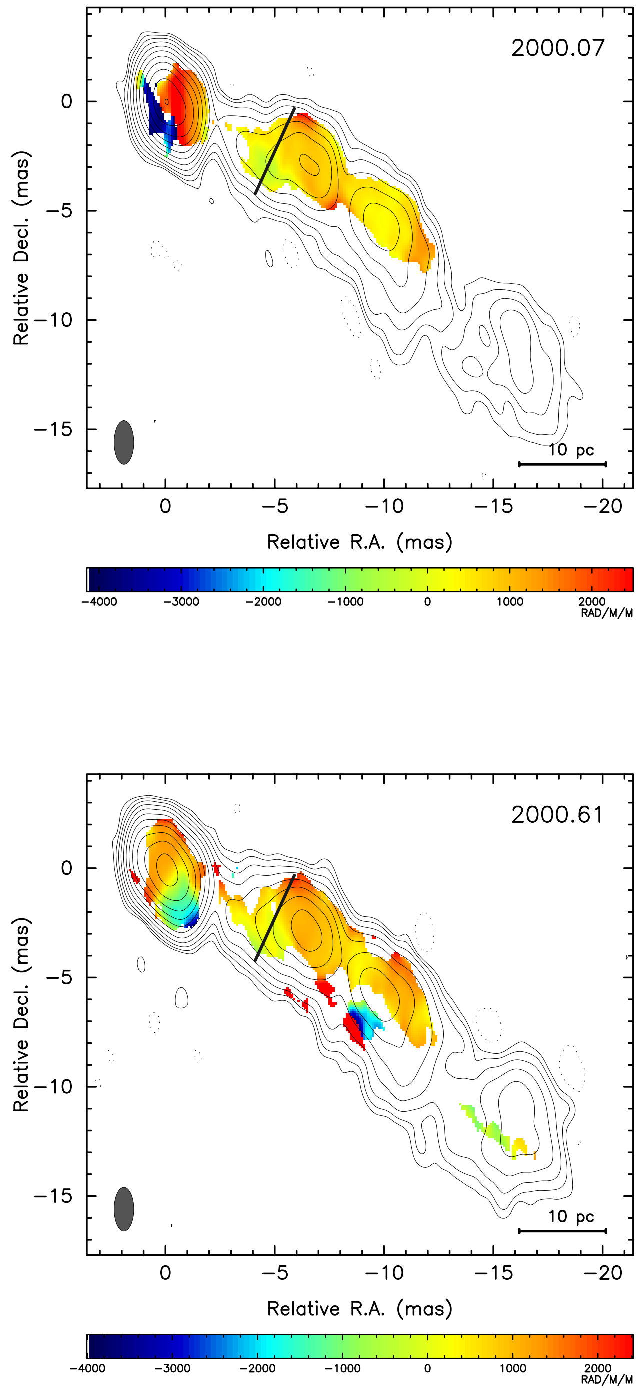

Fig. 1.— Rotation Measure image for 3C 273 on two epochs. Total intensity contours at 12.1 GHz are overlaid with contour levels starting at 12 mJy/beam and 6.6 mJy/beam for epoch 2000.07 and 2000.61 respectively and increase by factors of 2. The synthesized beam is drawn in the bottom-left corner and has dimensions of 2.0 × 0.9 mas at 0° for both epochs. The line indicates the location of the slices shown in Fig. 3.

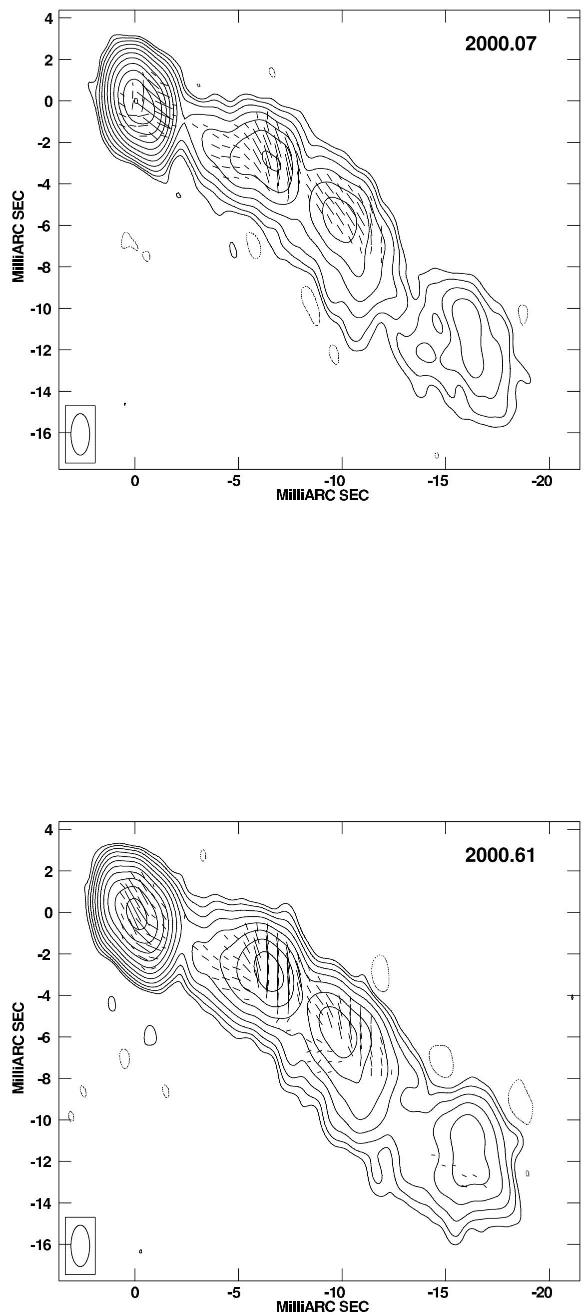

Fig. 2.— Rotation Measure corrected magnetic vectors for 3C 273 for our two epochs overlaid on total intensity contours. Contour intervals are the same as for Figures 1a and b. Lengths of magnetic vectors are proportional to the polarized intensity with scales of 1 mas = 100 mJy beam^{-1} for both epochs.

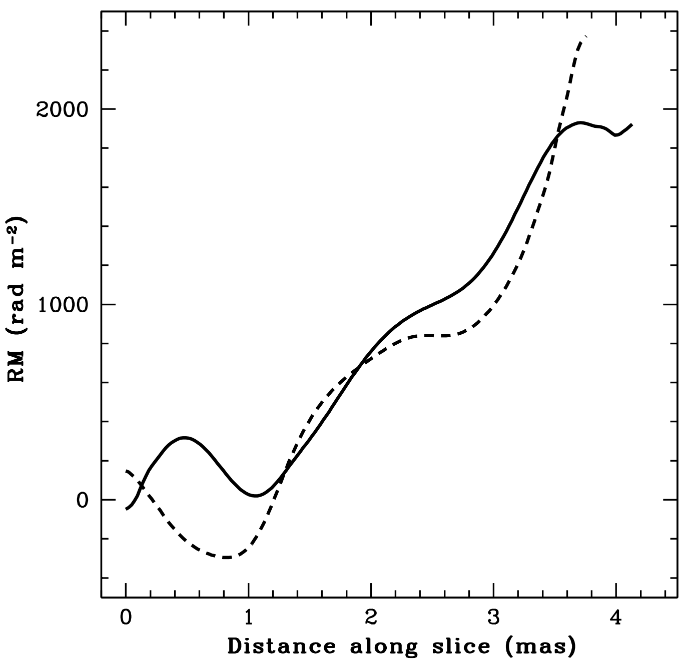

Fig. 3.— Rotation Measure image slices perpendicular to the jet axis for both epoch 2000.07 (dashed) and 2000.61 (solid). The region of the slice is indicated by the solid line in Fig. 1.

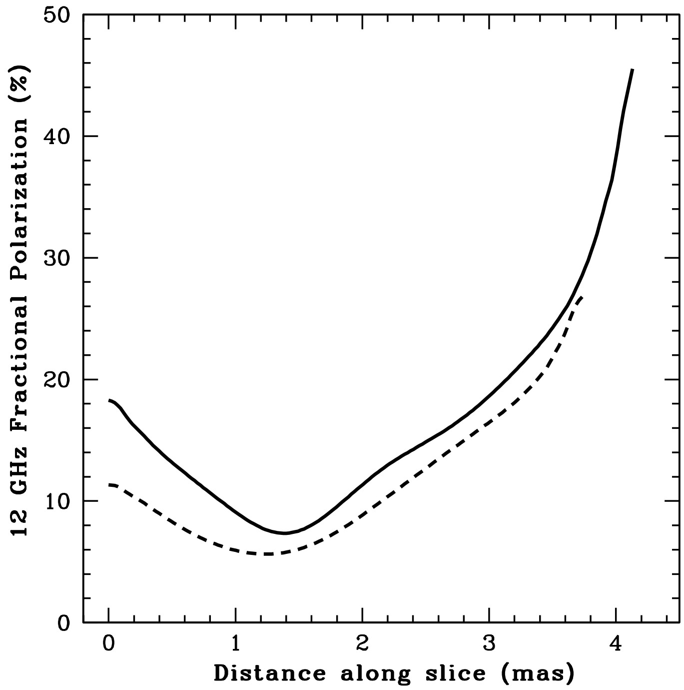

Fig. 4.— Fractional polarization slices perpendicular to the jet axis for both epoch 2000.07 (dashed) and 2000.61 (solid). The region of the slice is indicated by the solid line in Fig. 1.